

**BACKGROUND X-RAY EMISSION FROM HOT GAS
IN CDM AND CDM+ Λ UNIVERSES: SPECTRAL SIGNATURES**

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ABSTRACT

We present a new treatment of two popular models for the growth of structure, examining the X-ray emission from hot gas with allowance for spectral line emission from various atomic species, primarily “metals”. The X-ray emission from the bright cluster sources is not significantly changed from prior work and, as noted earlier, shows the CDM+ Λ model (LCDM) to be consistent but the standard, COBE normalized model (SCDM) to be inconsistent with existing observations — after allowance for still the considerable numerical modelling uncertainties.

But we find one important new result. Radiation in the softer band 0.5-1.0keV is predominantly emitted by gas far from cluster centers (hence “background”). This background emission dominates over the cluster emission below 1keV and observations of it should show clear spectral signatures indicating its origin. In particular the “iron blend” should be seen prominently in this spectral bin from cosmic background hot gas at high galactic latitudes and should show shadowing against the SMC indicating its extragalactic origin. Certain OVII lines also provide a signature of this gas which emits a spectrum characteristic of $10^{6.6\pm0.6}\text{K}$ gas. Recent ASCA observations of the X-ray background tentatively indicate the presence of component with exactly the spectral features we predict here.

Cosmology: large-scale structure of Universe – hydrodynamics – Radiation Mechanisms: Bremsstrahlung – Radiation Mechanisms: lines – X-ray: general

1. INTRODUCTION

In the three preceding papers, Kang *et al.* (1994), Bryan *et al.* (1994), Cen & Ostriker (1994 “LCDM”), we investigated the X-ray cluster properties in the standard COBE-normalized cold dark matter model and a CDM model with a cosmological constant, under the assumption that bremsstrahlung was the primary emission process. While this assumption is an excellent approximation for hard X-ray bands ($h\nu > 2\text{keV}$), which characterize the emission from the great clusters, its validity in softer bands has to be examined more carefully. In this paper, we include detailed X-ray line emissions from twelve major elements (He, C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, Ni), in addition to bremsstrahlung due to these elements, and we shift focus to the lower luminosity, lower temperature clusters, filaments and sheets that would normally be considered a part of the “X-ray background”. We compare the X-ray cluster luminosity functions and X-ray background radiation fields for two cases: with and without line emission at different bands, for both cosmological models. The issue of cooling flows in cluster centers is also addressed in an approximate fashion, and detailed X-ray spectra of a few bright X-ray clusters are presented. Finally, we compute the “background” emission from hot gas in the two models – the line and continuum emission from gas far from the centers of rich clusters. Our primary new result is that the extragalactic background radiation field due to hot gas far from the centers of rich clusters is surprisingly large and it dominates over other (diffuse) sources at energies below 1keV.

Very recent observations (Gendreau *et al.* 1994) of the spectrum of the X-ray background clearly indicate a thermal component from evidence for OVII and OVIII lines. The data also show “an excess above the extrapolation of the single

power law model below 1keV” of exactly the nature we describe in section 3.2.

In this paper we concentrate on the spectral signature of the background gas. A subsequent paper (Cen *et al.* 1995) will focus on the spatial distribution; we note here in anticipation of that paper that the angular autocorrelation function of the hot gas in our simulations does (due to the background gas component) show the extended features (up to several degrees) seen in the real data (Soltan *et al.* 1995).

This present paper is organized as follows: section 2 describes our method of including line emission processes, §3 gives the results and comparisons with observations, and our conclusions are assembled in §4.

2. METHOD

The cosmological models which we are investigating here are the same ones that we studied previously: 1) the standard, COBE normalized cold dark matter model (SCDM) with $\Omega = 1$, $H = 50\text{km/s/Mpc}$, $\sigma_8 = 1.05$, $\Omega_b = 0.06$ (Kang *et al.* 1994); 2) a COBE normalized, flat cold dark matter model with a cosmological constant (LCDM) with $\Omega = 0.45$, $\lambda = 0.55$, $H = 60\text{km/s/Mpc}$, $\sigma_8 = 0.77$, $\Omega_b = 0.043$ (Cen & Ostriker 1994). Both model simulations are performed in a box of size $85h^{-1}\text{Mpc}$ with 270^3 cells and 135^3 dark matter particles. These simulations were run in an adiabatic fashion, i.e., no cooling/heating processes were included except for shock heating, which is intrinsic to the simulations and hence automatically included. After the simulations were completed, we calculated line emission and continuum emission from heavy elements, in addition to those due to H and He, simply by assuming that the metals should be present in the cosmic gas, at the observed abundances. The excluded dynamic effect of

cooling/heating effect due to the metals, which are not present in the original simulations, is probably unimportant because the cooling/heating time is typically much longer than the dynamical time of the systems under consideration, as we will show below.

The X-ray clusters in the simulations are identified in exactly the same way as before; see Kang *et al.* (1994) for details. The metallicity in different (density) regions is assumed to have the following form:

$$Z(\rho_{sm}) = 0.35 \times (1 - e^{-(\rho_{sm}/\bar{\rho}_b)^2}) \quad , \quad (1)$$

where $Z(\rho_{sm})$ is in units of solar metallicity; ρ_{sm} is the baryonic density of the region in question smoothed over a Gaussian window of radius $1h^{-1}\text{Mpc}$, and $\bar{\rho}_b$ is the global mean of the baryonic density. This approximate formula is not intended to be very accurate, but it suffices to our needs. Equation (1) will produce for high density regions the metallicity observed in the great clusters, 0.35 (Edge & Stewart 1991; Arnaud *et al.* 1992,1994). Then for regions with a low density, ρ_{sm} , the metallicity declines rapidly, giving for gas in the voids ($\rho_{sm}/\bar{\rho}_b \approx 0.1$) a metallicity of $3.5 \times 10^{-2}Z_{\odot}$, consistent with estimates/bounds obtained from studies of QSO absorption lines (Fan & Tytler 1994; Cowie *et al.* 1995).

The X-ray emissivity is calculated with a code based on the work of Raymond & Smith (1977), which was kindly made available to us by J.C.Raymond. It is assumed that the gas is in ionization equilibrium and optically thin. The photoionization by the diffuse radiation is ignored for the present study, since collisional ionization dominates over photoionization for $T \gg 10^5 K$. The solar abundances are taken from the CLOUDY code (Ferland 1994): C (8.56); N

(8.05) ; O (8.93); Ne (8.09); Mg (7.58); Si (7.55); S (7.21); Ar (6.56); Ca (6.36); Fe (7.67); Ni (6.25). The He abundance is assumed to be 10.90, consistent with standard light-element nucleosynthesis. The emission rates from H, He and metals are calculated separately. Then each component is weighted by the relative abundance and the sum of all components is our total emissivity. We use the following energy bins to generate the spectra: 0.5 eV for $h\nu = 1 - 100$ eV, 5 eV for $h\nu = 100 - 1000$ eV, 20 eV for $h\nu = 1 - 10$ KeV, 40 eV for $h\nu = 10 - 50$ KeV, and 100 eV for $h\nu = 50 - 1000$ KeV.

3. RESULTS AND COMPARISONS WITH OBSERVATIONS

3.1 Luminosity Functions

Figures 1 and 2 show the X-ray luminosity function for clusters of galaxies in the two models considered: SCDM and LCDM. Figures 1a-d, for the SCDM model break the total luminosity into standard spectral bands and compare our previous results based on bremsstrahlung emission from a (H, He) plasma (solid squares) to the full (line and continuum emission (open circles) from a CLOUDY (Ferland 1994) mixture of elements. Two points are to be noted. First, for high luminosity clusters ($L_x \geq 10^{44}$ erg/s) the differences are minimal, becoming significant (\geq factor of three) only at the lowest luminosities ($L_x \approx 10^{41}$ erg/s), where our observational knowledge is poor. This is simply a manifestation of the temperature luminosity relation noted in both observations (Edge *et al.* 1990; Henry & Arnaud 1991; Henry 1992) and in the numerical simulations (Cen & Ostriker 1994). At lower luminosities the clusters have lower temperatures, leaving the atoms less fully ionized and more capable of line emission. Second, the differences are least in the hard bands such as the 1-10keV range (Figure 1d) and

most in the bands shown in Figures 1b and 1c which reach below 1keV, where the principal line emission occurs.

Figures 2a-2d show the same simulated data from the LCDM model and show the same differences between continuum only and line plus continuum computations. The increase due to line emission is greater for LCDM than for SCDM, since the LCDM clusters are cooler. Overall, our prior conclusions that SCDM over-predicts the number of bright X-ray clusters but LCDM is in rough agreement with observations remains true, as the high luminosity clusters, where comparisons to observations are cleanest, are not much effected by line emission.

3.2 Spectral Energy Distributions

Figures 3 and 4 show detailed spectra for the two models broken up in a different way. All the luminosity emitted in the box from regions within a $1h^{-1}\text{Mpc}$ of the center of a rich cluster having $L_x(\text{bolometric}) > 10^{43}\text{erg/s}$ is shown (the solid line) as the mean spatial emissivity due to “X-ray clusters” in $\text{erg/cm}^3/\text{se/eV}$. But much of the hot, emitting gas is further from cluster cores, or in poor clusters or groups, or along filaments and sheets. These regions typically have such a low surface brightness that current and planned instrumentation does not detect them as distinct “sources”. But they should be seen in all sky studies and will have specific spectral and angular distribution features. The gas causing this residual emission is, of course, highly clumped but it fills a much larger fraction of the total volume than the $(1.8 \times 10^{-4}, 6.4 \times 10^{-5})$ filling factor occupied by the luminous clusters, in (SCDM,LCDM) models respectively. This gas is also, of course, typically at a lower temperature than the several keV gas in the great clusters. In Figures 3a and 3b the dashed lines show the volume-

averaged emissivity from this “background” gas. The upper panels (3a,3b) show the spectra at a resolution which roughly corresponds to the ASCA experiment (Tanaka, Inoue, & Holt 1994) with the relative displacement of curves shown as computed. The lower panels show the same information with arbitrary shift of the vertical scale and higher resolution on the horizontal scale to allow better identification of individual lines and to indicate what future experiments may find.

We note that in both models the background hot gas dominates over the emission from rich clusters below approximately 1keV. Since our problems of spatial resolution are more severe for the smaller structures producing the background than they are for computing the properties of the great clusters, we expect that an accurate calculation might increase the cluster emissivity by perhaps a factor of two and the background by at least a factor of four, leading to still greater dominance of the background gas in the range $10\text{eV} < h\nu < 10^3\text{eV}$. The ratio is larger for the LCDM model than for the SCDM model, because the former has relatively lower temperatures.

The steepening of the spectrum below 1keV seen recently by ASCA (*cf.* Gendreau *et al.* 1994) as well as the OVII lines (also noted by ASCA) discussed below are tentative but direct observational evidence that the background gas we are discussing has already been detected.

This new component of soft X-ray emitting gas is only apparent when we allow properly for line emission. For example, if in Figure 4a, we artificially assume zero metallicity for the background gas we reduce the luminosity in the 10-1000eV by a factor of 3.1. The spectral signature of the background as seen in the low resolution spectra, Figures 3a and 4a is the “iron bump” (actually a

mixture of iron and oxygen) in the region 0.5-1.0keV.

Now let us turn to Figures 3b and 4b which show detailed spectra that allow us to identify better those spectral lines which are contributing most to the background. We see in the background gas a strong signature in the 0.561-0.574keV (marked with “*”) range from a blend of OVII lines (characteristic of 10^6 K gas) that is weak or absent in the clusters emission spectra. Also strong in the background gas is the 0.904-0.922keV blend of lines from NeIX at a similar temperature. Both features are nearly absent in the cluster gas. The strong OVIII line at 0.654keV (marked with “o”) seen in both cluster and background gas will give a separate indication of oxygen abundance allowing the ratio of the 0.57keV to the 0.65keV features to be used as a temperature indicator. We have found one other spectral feature, which is prominent in the background gas, but is absent from the cluster spectra. This is a pair of iron XVII lines at 0.726keV and 0.739keV (marked with “x”) which have peak strength in gas at approximately $10^{6.5}$ K. These are strong in the lower (background) dashed curves of Figures 3b and 4b, but are not apparent in the cluster gas, where all the strong Fe lines are from higher ionization species, typically Fe XIX→ Fe XXII.

Figures 5a,b show typical spectra (from the LCDM model) for a high temperature (2.7keV) high luminosity (1.6×10^{44} erg/s) cluster and a lower temperature (1.8keV) lower luminosity (3.5×10^{43} erg/s) cluster. Overall, line emission is stronger in the lower temperature cluster particularly the ~ 1 keV iron blend and the 0.654keV OVIII line.

How can the background gas that we are discussing be distinguished from the hot Galactic gas along the same line of sight? To some extent the soft X-ray “background” that we are proposing is the same as Galactic emission in that

the sum over all galaxies like our own does make a nontrivial contribution to the soft X-ray background. If the average galaxy emits 2×10^{39} erg/s in the 0.5-1.5 keV band (*cf.* Fabbiano 1989), then the sum of all such will produce an emissivity of 10^{-39} erg/cm³/sec/eV not far from the levels shown in Figure 4a. But most of the emission shown by the dashed line in 4a is due to hot gas in bigger systems than our own galactic disk or halo. Thus, the temperature is in the range $10^6 - 10^7$ K, whereas, for most of the galactic coronal gas, the typical temperature (as weighted by ρ^2) is in the range $10^5 - 10^6$ K. Thus, the line ratios indicative of the OVI/OVII and OVII/OVIII ratios will help in distinguishing between the two components. The mean logarithmic slope of S_ν will also provide an important discriminant, in that the background emission shows a much steeper slope than the cluster emission below 1 keV.

But both the line ratios and the slope of the continuum will be effected by the convolution over redshift, i.e., we see along any line of sight radiation emitted at a variety of epochs shifted by various amounts. However, this effect, which will blur out line features, is not as large as might be expected. Examination of Figure 14 of the LCDM paper shows that in even the softer (0.3-3.5 keV) band half of intensity arises from redshift of less $z = 0.32$. Thus, the mean redshift of the emitted ~ 1 keV photons will be close to $z = 0.32$ with a dispersion of perhaps $\sigma = 0.32$. As a consequence, the blurring of spectral features in the background will be approximately $0.2/1.3=24\%$ with a shift of 32%. Specifically the iron blend should move from the region 0.6-1.0 keV (FWHM) to the region 0.45-0.81 keV with a width only slightly larger than shown in Figure 4a.

In fact, a strong soft X-ray background radiation field has been detected (see McCammon & Sanders 1990) but, for a variety of reasons, the very low energy

part of this is believed to be of Galactic rather than extragalactic origin. For example, in the C-band, 0.2-0.3 keV, the minimal shadowing of the soft X-ray background by SMC (recently reviewed by McCammon & Sanders 1990) seriously limits the extragalactic component, showing that a large fraction originates from a hot component of the ISM (*cf.* McKee and Ostriker 1977), or a hot galactic halo. But there are reasons to believe that a significant fraction of at least the component in the range 0.5-1.0keV is truly extragalactic (*cf.* Burrow & Kraft 1993; Gendreau *et al.* 1994). The spectral features which we noted earlier should help provide clues to the origin of the background radiation in this range as the galactic component is probably too cool to produce the iron blend which should be prominent in the background component described in this paper.

3.3 Cooling Cluster Cores

Now let us turn to the question of cooling flows. There is abundant evidence (Fabian 1994) that in the central regions of many clusters substantial amounts of gas exist that have cooling times which are short compared to the Hubble time. We have not addressed this issue in the past for two reasons: first, since we did not include metal line emission, our cooling functions were inaccurate in just those regions where cooling might be most important; and, second, our spatial resolution was inadequate to examine accurately the dense central regions which are most likely to cool. We can address the first of these issues now, but our resolution, while improved over our earlier calculations, is still not sufficient to address the problem accurately so our remarks must be confined to comparative issues. For which models and which luminosity ranges is cooling of greatest importance? Figures (6) and (7) show the ratio of the Hubble time to the cooling

time for the central cell in each cluster, the first figure showing the distributions of this ratio for the SCDM model and the second the distributions for the LCDM model. The volume of the central cell is $(315h^{-1}kpc)^3$ which corresponds to a sphere of radius $195h^{-1}kpc$. Given the unavoidable numerical diffusion, a more accurate estimate of our effective central cell radius might be approximately $250h^{-1}kpc$. In both Figures (6) and (7) we divide the clusters into three groups based on the total bolometric luminosity. We see that for the highest luminosity clusters ($L_{bol} > 10^{43} \text{erg/s}$) the computed cooling times are very long on average compared to the Hubble time. For the SCDM model t_H/t_{cool} is always less than 0.03 and for the LCDM model it is less than 0.06. However our computed sample size is small and it seems likely that the tail would reach to a value of t_H/t_{cool} which is factor of 10 higher were the sample size to include 100 bright clusters. This issue of a small statistical sample plus our relatively poor resolution make it likely that perhaps a few percent of the bright clusters would have cooling cores in perfect simulations of these two models. Work currently in progress should greatly clarify this issue.

But we can say with some certainty that the lower luminosity clusters, since they have lower temperatures, cool much more efficiently. This is especially evident in the LCDM model (Figure 7c), where it is clear that cooling would be an important effect for higher resolution simulations.

The trend for the increased importance of cooling in Figures (6) and (7) as we go from (a) \rightarrow (c) is evident (low luminosity regions are more subject to cooling than high luminosity regions) and strengthens the conclusions of section (3.1). When cosmic gas cools, it typically contrasts to a higher density and thus cools still more rapidly. Thus, if we had allowed for cooling in the evolution

of the gas, then the background emission that we found would have been still stronger with respect to the average cluster emission.

4. CONCLUSIONS

Straightforward physical theory predicts that the gravitationally induced growth of structure will lead to an accumulation of hot shocked gas at the vertices where caustics intersect. Numerical simulations have in fact confirmed that some models for the growth of cosmological structure do fit rather nicely the X-ray observations of clusters of galaxies. However the same theories also predict the existence of much more hot gas, at a somewhat lower temperature, filling a significant fraction of cosmic space with X-ray emitting sheets and filaments. In this paper we compute the spectral properties of this “background” gas noting that it should dominate over the cluster gas (in total emissivity) at energies below 1keV.

Figures (8) for SCDM and (9) for LCDM summarize the nature of the regions emitting the two components at redshift zero, the upper panels showing the volume weighted distribution of ρ^2 (as a function of gas temperature) and the lower panels the emissivity-weighted ($\int_{200\text{eV}}^{10\text{keV}} S_\nu d\nu$) distribution. Examining Panel (9b) we see that the cluster X-rays are typically emitted from gas in the range $10^{7.0-7.8}\text{K}$ whereas the background gas emission is broadly distributed in the range $10^{6.0-7.3}\text{K}$. The signature of the background gas will be softer spectrum, certain specific lines and blends, and a spatial extent which is much more diffuse (in terms of angular autocorrelation function) than the cluster gas. The long standing problem that the spectrum of the background does not match well to the spectrum of the resolved sources remains with us. Further as pointed out

by Hasinger *et al.* (1993) and earlier by Hamilton and Helfand (1987) there is room, even perhaps a necessity for either a very faint unclustered population of sources or a more smoothly distributed component. Also recent ASCA measurements (Gendreau *et al.* 1994) indicate the existence of a background component with a steep spectrum below 1keV and evidence from OVII lines. Thus, it may be that ROSAT, ASCA and other satellites have already observed the emission from this background gas but, because of its diffuse nature, rather specific analyses of the observational data must be undertaken to confirm the detection.

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FIGURE CAPTIONS

Fig. 1– Figures (1a,b,c,d) show the computed luminosity functions in four different bands: bolometric, $0.3 - 3.5\text{keV}$, $0.5 - 4.5\text{keV}$, $2 - 10\text{keV}$, respectively, for the SCDM model at $z = 0$. The open symbols include line emissions as well as bremsstrahlung; the solid squares include only bremsstrahlung due to H and He. The hatched region in Figure (1a) indicates observations by Henry and Arnaud (1991) and that in (1d) the observations of Henry (1992).

Fig. 2– Analogous to Figure 1 but for the LCDM model.

Fig. 3– Panel (a) shows volume-averaged X-ray emissivity of all the bright clusters $L_{bol} > 10^{43}\text{erg/s}$ (solid curve) and X-ray emissivity of the background (dashed curve) at redshift $z = 0$ for the SCDM model. We use the spectral resolution of ASCA SIS detector, which has resolution of 60 eV at 1 keV and 140 eV at 8 keV (linear interpolation is used for the range 0.4 keV to 9 keV which SIS detector is sensitive, below 0.4keV we simply assume a spectral resolution of 60eV). Panel (b) shows a high resolution version of panel (a) with the two curves displaced vertically by an arbitrary amount for display purpose. Note the prominent “iron bump” in the background emission. In panels 3b and 4b of the high resolution spectrum we designate three temperature sensitive lines by “*” (from an OVII blend characteristic of 10^6K gas at $0.561 - 0.574\text{ keV}$), by “o” (from OVIII of $10^{6.5}\text{ K}$ gas at 0.654 keV) and by “x” (a pair of iron XVII lines at 0.726 keV and 0.739 keV from gas at $10^{6.5}\text{K}$).

Fig. 4– Analogous to Figure 3 but for the LCDM model. Note how the background emissivity dominates over the radiation from clusters below 1keV .

Fig. 5– Figures (5a,b) show two spectra of two bright X-ray clusters in the LCDM model.

Fig. 6– Figures (6a,b,c) show histograms of the ratio t_{Hubble}/t_{cool} for X-ray clusters in three different luminosity bands, in the SCDM model.

Fig. 7– Analogous to Figure 6 but for the LCDM model. Cooling should be important in low luminosity clusters.

Fig. 8– Figure 8 shows a plot of ρ^2 on the cell scale as a function of temperature in two different ways: volume-weighted (top panel) and weighted by emissivity ($\int_{200\text{eV}}^{10\text{keV}} S_\nu d\nu$) (bottom panel), for the SCDM model at $z = 0$. Each panel is further broken into two different components: clusters and background. Note that the background radiation is emitted by considerably lower temperature gas than that producing the cluster emission.

Fig. 9– Figure 9 is the same as Figure 8 but for the LCDM model.